



Determination of zones suitable for the exploitation of the Oued Khairat aquifer (Tunisian Sahel)

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Received: 19 November 2021 / Accepted: 5 January 2023 / Published online: 12 January 2023
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Abstract

This study presents complementary approaches for enhancing the groundwater management in the Enfidha region (Tunisian Sahel). It integrated and analyzed geological, hydrogeological, well logs, and hydrochemical data for a better characterization of the Oued El Khairat aquifer; its geometry, hydrodynamics, and water quality were well-defined. The geometry was determined from the lithological columns and well logs analysis and correlations. Well logs allowed a precise delimitation of the Mio-Plio-Quaternary permeable layers, thus facilitating the creation of two- and three-dimensional representations elucidating the water reservoirs arrangement. These representations highlight that coarse deposits are more abundant in the western part of Oued El Khairat plain than in its eastern part. The aquifer hydrodynamics was studied using piezometry and transmissivity data. The piezometric maps indicate a main groundwater flow from the west to the east. The transmissivity measures vary between $1.2 \cdot 10^{-4}$ and $1.56 \cdot 10^{-2} \text{ m}^2/\text{s}$. The permeability coefficients, derived by subdividing these measures by the aquifer thicknesses, are relatively higher ($0.73 \cdot 10^{-4}$ and $4.3 \cdot 10^{-4} \text{ m/s}$) in the center-east part of the plain. The water quality is assessed through the salinity and chemical composition data. The salinity map shows values ranging from 1.5 to 3.1 g/l with gradual increase according to the groundwater flow direction (from the west to the east). Hydrochemical analyses show that the majority of water samples present sulfate facies. The results highlighted that the western and central-eastern parts of Oued El Khairat plain are the most suitable zones for the exploitation of this aquifer.

Keywords Oued El Khairat aquifer · Tunisian Sahel · Better characterization · Geometry · Hydrodynamics · Water quality

Introduction

In the last decades, population growth, socio-economic development, and climate change have been remarkably depleting water resources, thus generating the most serious problem that threatens the humanity (Mendonça 2004; UNESCO 2015; IPCC 2018; Masson–Delmote 2020; UN-Water 2021). Tunisia, located in North Africa (Fig. 1a) is among the forty-four countries presenting

“high” levels of water stress, where on average more than 40% of available supply is withdrawn every year (WRI 2019). Aware such situation, it has adopted since 1970 a water polity aiming the equilibrium water need–water availability (Treyer 2002) and whose main actions are (Ayadi 2017): (1) better knowledge of resources; (2) mobilization of the recognized resources; (3) economy and rational exploitation of water; (4) use of unconventional water (seawater desalination, wastewater treatment...); (5) prevention and control of water resources pollution.

A factual example is exposed by the present publication resulting from cooperation between the Water Research and Technology Center (CERTe) and the Regional Commissariat of Agricole Development (CRDA) of Sousse. It implicated different disciplines—geology, hydrogeology, geophysics, hydrochemistry, and geomatics to refine the knowledge of the aquifer system in Enfidha region (Tunisian Sahel) (Fig. 1b) and consequently determine suitable areas for the exploitation of the Oued El Khairat aquifer, which

Responsible Editor: Anis Chekirbane

This article is part of the Topical Collection on Water Quality, Global Changes and Groundwater Responses

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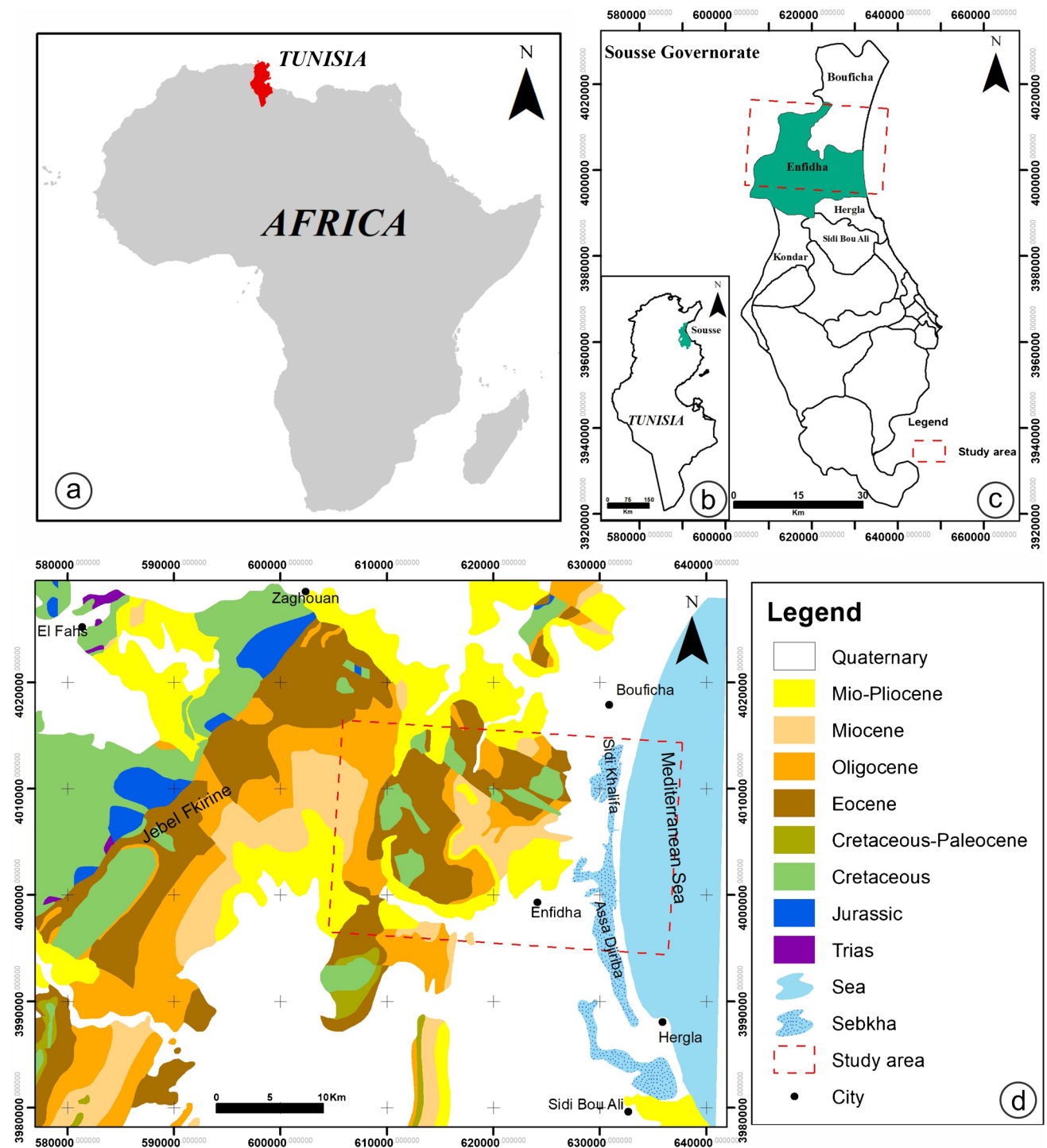


Fig. 1 Location of the study area at different scales. a. Tunisia. c. Sousse governorate. d. Localities bordering the study area (extract from the 1/500 000 geological map of Tunisia (Ben Haj Ali et al.1985)

constitutes with Chegarnia–Sidi Aibiche aquifer, the most important regional groundwater resources.

Hydrogeological works covering the entire Enfidha region (El Batti 1974; Horriche et al. 2013; Zammouri et al. 2013). They were mainly focused on the Oued El Khairat aquifer

(Manaa et al. 1996; Chadly 2002; Zammouri et al. 2006; Ketata et al. 2011; 2014; Chekirbane et al. 2021). Artificial recharge and its impact on this aquifer hydrodynamic and hydrochemical characteristics is the most considered subject. It is treated by Aloui et al. (2021) for Chegarnia–Sidi Aibiche aquifer.

Geographical, geological, and hydrogeological contexts

Enfidha is a coastal agricultural region occupying the northern part of Sousse Governorate (Fig. 1c). It is limited by Bouficha to the north, Sidi Bou Ali to the south, Jebel Fkirine (part of the Zaghouan Governorate) to the west and Mediterranean Sea to the east (Fig. 1d). It is marked by two evaporitic depressions: Sabkhet Khlifa in the north and Sabkhet Assa Djribia in the south. Its climate is semi-arid with annual precipitation varying between 300 and 400 mm/year (INGREF 2000).

Geologically, Enfidha region is shared between two different structural domains in Tunisia: the Atlasic domain in the north and the pelagic platform in the south (Fig. 2a). The northern Atlasic domain corresponds to a folded and faulted domain constituted of plenty NE-SW anticlines and NW-SE grabens (Jauzein 1967; Turki 1985; Ben Ayed 1986; Chihi 1995; Ben Chelbi 2007; Mzali 2010), while the pelagic platform is a relatively tabular area without significant reliefs. Geophysical data have identified complex structures in its subsurface (Haller 1983; Ellouze 1984; Bédir 1995 Gabtni 2005; Boussiga 2008; Hezzi 2014; Belkhiria et al. 2017).

Different tectonic structures characterize the Enfidha region (Fig. 2b). Jebel Mdeker, located in the northwestern zone, is a large anticline divided into three distinct compartments by three major meridian faults (Castany 1951). It is bordered to the west by the Saouef syncline eastern flank, oriented N25 and composed of Oligocene deposits (Banjanik et al. 1978; Briki 2013). The northeastern zone corresponds to the highly faulted structure of Jebel Abid (Lajmi and Biely 1974); faults with different directions compartmentalize this dome in several horsts and grabens. The NE-SW synclinal structure of Chegarnia-Sidi Abiche occurs in the center-east, while the Jebel Garci marks the center-west zone. It is truncated by major faults, mainly oriented NW-SE and E-W (Meddeb 1986; Saadi 1990).

The geological outcrops have different ages ranging from Jurassic to Quaternary in age (Fig. 2c).

The Jurassic deposits, restricted to Jebel Mdeker core (Fig. 2b), are composed of dolomites and marly limestones. The Cretaceous sediments outcropping at Jebel Mehjoul, Jebel Mdeker, Jebel Garci, Jebel Mania, Jebel Akera, Kef Nsoura, Jebel Bou Sefra, and Jebel Abid are made up of marls and limestones with sandstones and quartzites at the base. Marly outcrops mainly recognized at Jebel Garci, Jebel Mdeker, and the southwestern extremity of the study area represent the Paleocene. The Eocene series is widely exposed (Fig. 2b). Its lower part is constituted of Globigerina limestones, whereas its upper part consists of marls with limestone intercalations. The Oligocene outcrops extending mostly along the Saouef syncline border are made up of

sandstones, marls, and clays with sandy and gypsum intercalations. Encountered in the central and western parts of the Enfidha region (Fig. 2b), the Miocene series is composed of sands, sandy clays, limestones, conglomerates, gypseous clays, and sandstones interbedded by clay beds. The Mio-Pliocene deposits, scattered throughout the study area, are constituted of red sandy marls, coarse sands, and conglomerates. Scree, Sebkha, soils, dunes, actual beaches, alluvia, and terraces constitute the Quaternary sediments covering the eastern part of the Enfidha region.

Two main Mio-Plio-Quaternary hydrogeological systems characterize the study area: Oued El Khairat and Chegarnia-Sidi Abiche aquifers (Fig. 2b). They are recharged by rainwater infiltration, essentially into river beds (Oued el Breck, Oued Sidi Abiche, Oued El Khairat) (El Batti 1974; Manaa et al. 1996; Horriche et al 2013). According to the reservoir's depth, each aquifer comprises shallow and deep water tables, respectively exploited by surface wells (do not exceeding 50 m depth) and boreholes (deeper than 50 m). The resources of the Oued El Khairat and Chegarnia-Sidi Abiche shallow water tables were evaluated respectively to 0, 95, and 1, 8Mm³/year (DGRE 2015). Those of Chegarnia-Sidi Abiche are intensely exploited through 389 surface wells.

Concerning the deep water tables, the estimated resources are more elevated for Oued El Khairat aquifer (5, 6 Mm³/year) than Chegarnia-Sidi Abiche aquifer (1, 7 Mm³/year). The annual withdrawals are generally in equilibrium with the available volumes. Exceptional augmentation of exploitation was recorded during the period 2012–2014 for the Chegarnia-Sidi Abiche aquifer and in 2018 for the Oued El Khairat aquifer (e.g., DGRE 2018).

Data and methodology

Data acquired at 59 water boreholes exploiting the Oued El Khairat aquifer and 12 piezometers monitoring this aquifer were used in this study (Fig. 3). They comprise lithological columns and their corresponding well logs as well as hydrodynamic (transmissivity and piezometry) and hydrochemical (water salinity and chemical composition of major elements) measures.

Wells logs consisting mainly of gamma ray (GR) and resistivity logs were analyzed for a more accurate lithology description and precise delimitation of reservoirs' layers. Clays expressing low resistivity values have high radioactivity values given their richness in radioactive elements (Desbrandes 1985; Asquith and Gibson 1982; Chapellier 1992; Bassiouni 1994; Doveton 1994). Reservoir formations (gravels, sands, limestones) exhibit low radioactivities (Luthi 2001), while their resistivities are enormously

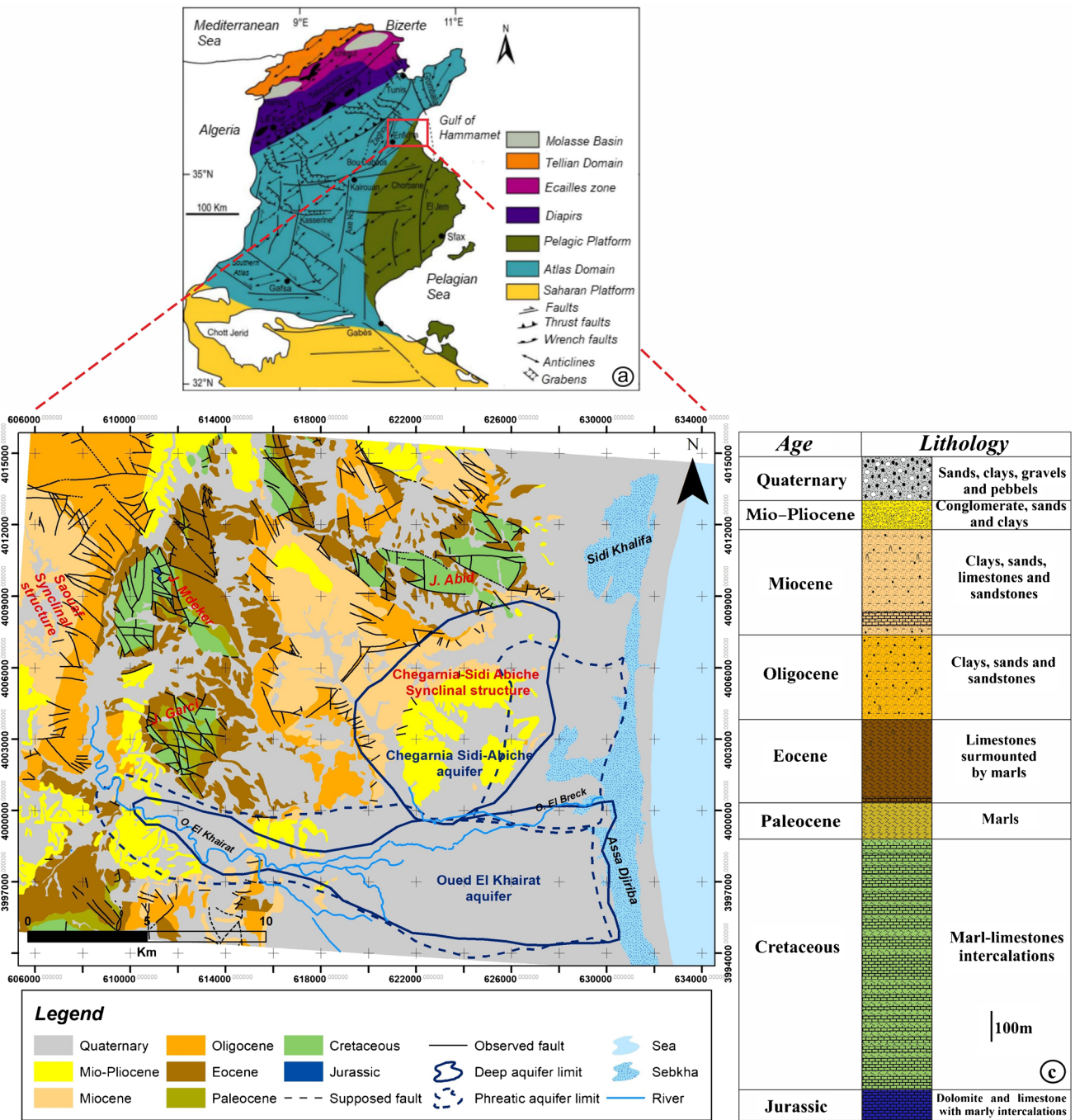


Fig. 2 Geological and hydrogeological contexts of the study area, (a) structural location (extract from structural map of Tunisia (Ghanmi 2003), (b) geological map (Lajmi and Biely 1974; M'hadhbi 2003)

and main alluvial aquifers (Agricol map of Sousse governorate), and (c) synthetic log of sedimentary series

influenced by the quality of water imbibition (Heurteaux 1988; Glover 2012; Liu 2017). Thus, we have focused our analysis on the GR logs since they reflect the lithological composition better than the resistivity logs.

In the geographic information system (GIS), more and more applied in hydrogeological studies (e.g., Gogu et al. 2001; Trabelsi et al. 2006; Jourda et al. 2015) were used

to process the available data (Fig. 4) and identify the main characteristics of the aquifer such as its geometry, hydrodynamics, and water quality.

The geometry of the Oued El Khairat aquifer were determined from the restored lithological logs, which were subdivided into clayey and predominantly coarse units to make easier the elaboration of three-dimensional representations

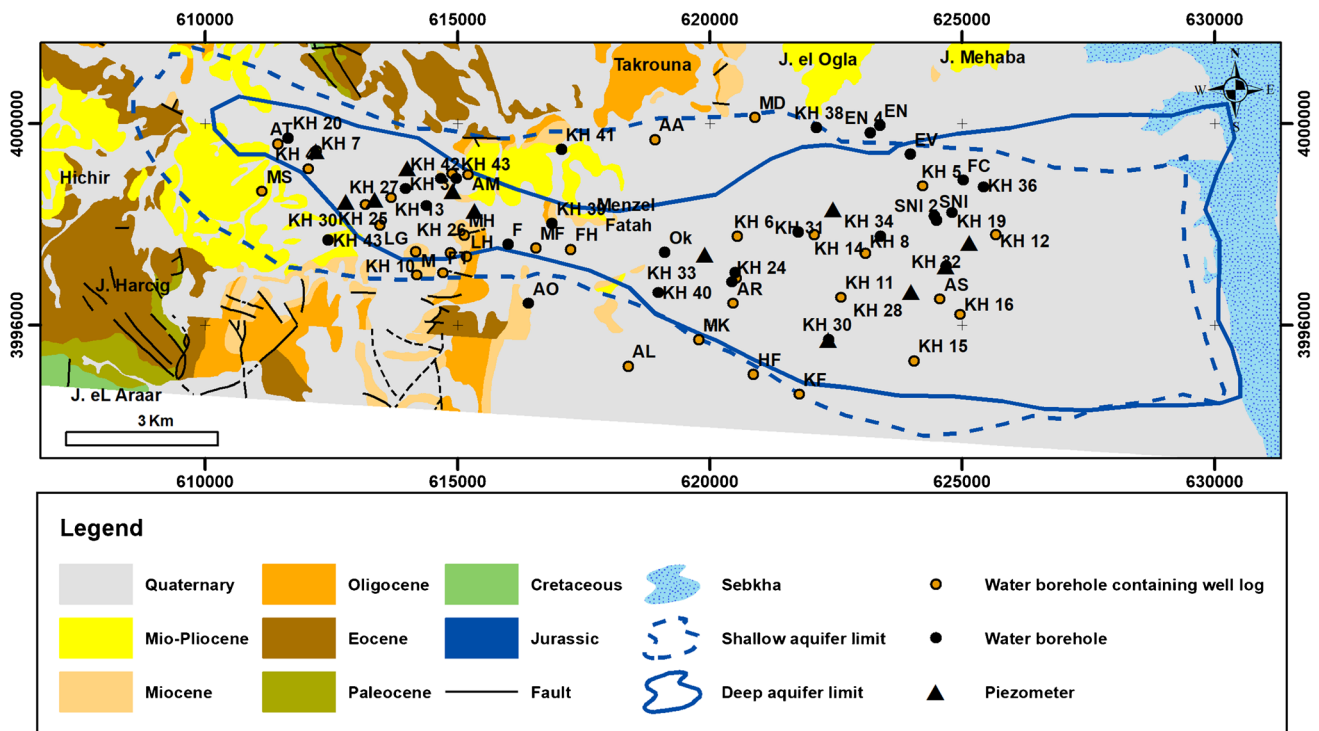


Fig. 3 Distribution of water boreholes and piezometers relating to the Oued El Khairat aquifer

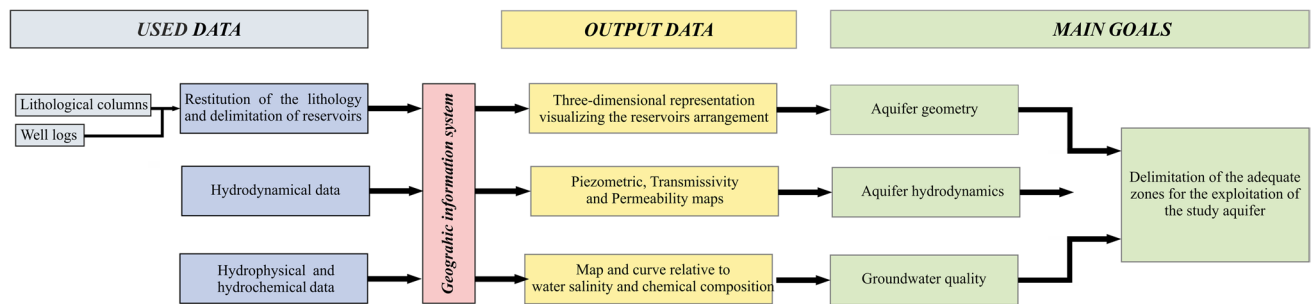


Fig. 4 Adopted methodology to exploit borehole data for the determination of suitable areas for the Oued El Khairat exploitation

showing the reservoir formations arrangement. Furthermore, we have established a reservoir abundance map, after calculating the percentage of coarse formations in the intersected Mio-Plio-Quaternary series. Independently of the boreholes depths, we have retained a common thickness of 100 m for this series.

Transmissivity (*T*) and piezometric data were exploited to study the aquifer hydrodynamics. These parameters assessment is crucial to apprehend the functioning of an aquifer and evaluate its reserves (Nemeth and Solo-Gabriele 2003; Caballero et al. 2007; Cao et al. 2019).

Concerning groundwater quality, it was evaluated via salinity measures and chemical composition analyses, which were represented in the form of maps, curves and diagrams.

At the final stage, the different thematic layers reduced representations relating to the geometry, hydrodynamics, and water quality were confronted and superposed to delimit the suitable zones for the exploitation of the Oued El Khairat aquifer.

Results and discussion

Geometry of the Oued El Khairat aquifer

In Oued El Khairat plain, the differentiation between the Miocene and Plio-Quaternary deposits in the different water boreholes is difficult, given the similitude of lithologies

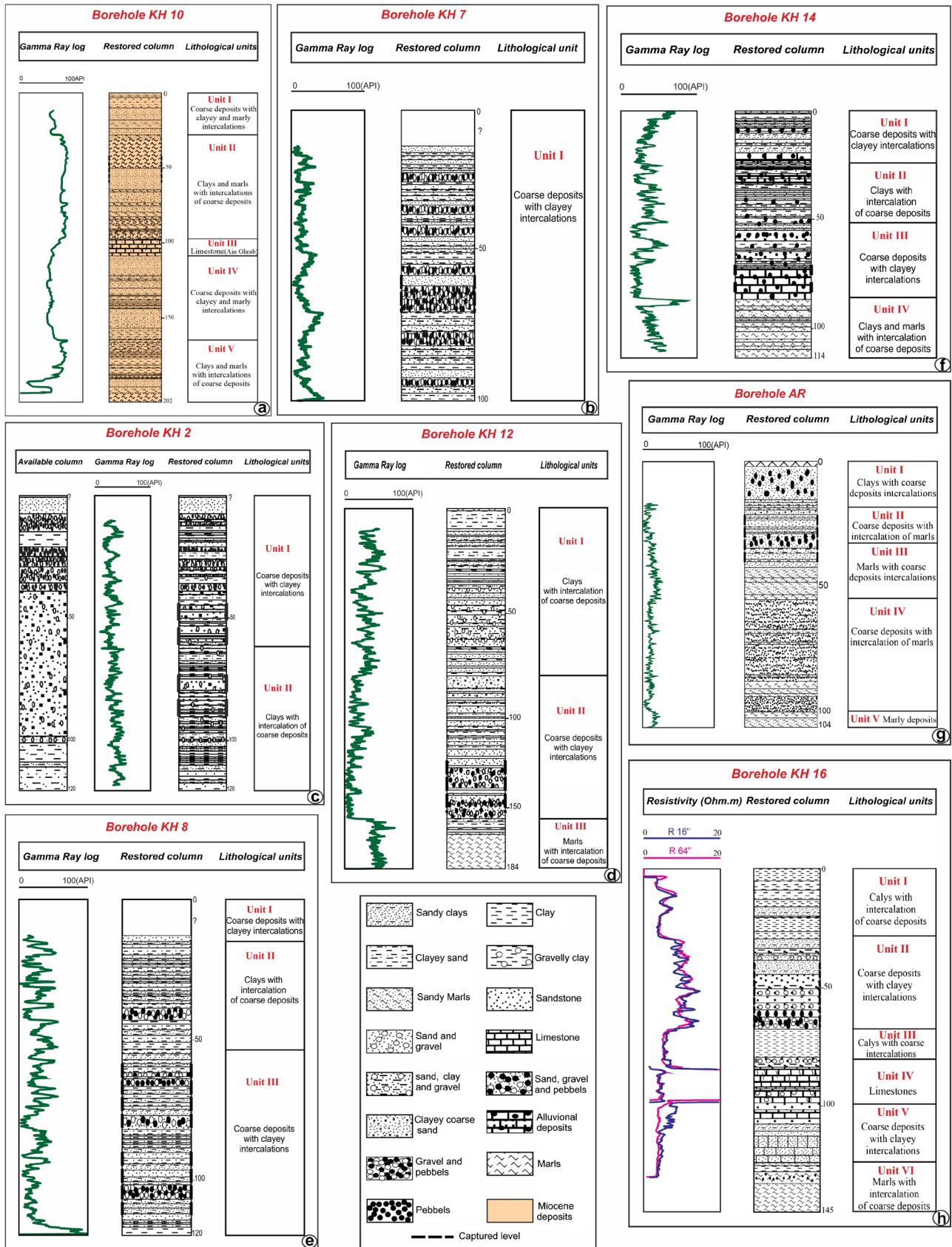


Fig. 5 Examples of the analysis of borehole well logs. (a) Borehole KH 10 (Amri and Bouasker 1994), (b) borehole KH 7 (Chadli 2000), (c) borehole KH 2 (DGRE 2000), (d) borehole KH 12 (Chadli and Sehli 2000), (e) borehole KH 8 (Chadli 2007), (f) borehole KH 14 (El Batti et al. 1979), (g) borehole AR (Trabelsi 2008), (h) borehole KH 16 (Khaoudja and Kaddeche 1966)

characterizing these deposits. However, we are sure that KH 10 (202 m depth), M (82 m depth), MH (45 m depth), and LH (90 m depth) boreholes represent Miocene series since they are implanted on outcrops of this series.

Well logs analysis allowed accurate distinction between permeable and impermeable layers within Miocene to Mio-Plio-Quaternary deposits in Oued El Khairat plain. Clayey and predominantly coarse formations varying in number, arrangement, and thickness have been defined.

KH10, the deepest borehole (202 m) among those intersecting Miocene deposits, exposes through its lithological column and gamma ray log seven lithological units composed of three coarse units identified between 0–27 m, 54–73 m and 108–165 m, three clayey–marly units detected between 27–54 m, 73–98 m, and 165–202 m and a limestone unit constituting the Ain Ghrab Formation, which is Miocene in age (Fig. 5a).

Undifferentiated Mio-Plio-Quaternary series may be composed of one to six lithological units. Indeed, in the KH 7 (Fig. 5b) and KH9 boreholes, the totality of this series is represented by a reservoir formation. The KH2, KH 4 (Fig. 5c) and KH 6 boreholes reveal a coarse unity overlying a predominantly clayey unit. Equally, the KH3, KH5, and KH12 boreholes show a single permeable formation, but between clayey and marly units (Fig. 5d). Contrary, in the KH1 and KH8 boreholes, a clay unit separates two coarse formations (Fig. 5e). An additional impermeable formation is defined in the KH14 and KH15 boreholes, which reveal on the whole four lithological formations (Fig. 5f). Five formations were identified in the AR borehole: three of them are clayey and two are coarse (Fig. 5g). They are interbedded by a limestone unit in the KH16 borehole (Fig. 5e). The age of this unit isn't indicated in the borehole report (Khaoudja and Kaddeche 1966).

The reservoir abundance map (Fig. 6a) reveals that in the majority of water boreholes, the coarse units constitute between 50 and 75% of a 110-m-thick Mio-Plio-Quaternary series. The highest percentages (75 to 100%) are mainly encountered in the western part of the plain. They may be explained by the fact that this zone corresponds to the upstream of Oued El Khairat. In fact, in a watercourse, the current velocity decreases from upstream to downstream inducing upward–fining of the transported elements; the coarsest were firstly deposited in the upstream where the current is strong (Briot 1981; Ballais et al. 1999).

The 3D lithological model (Fig. 6b) resulting from the correlation between the restored lithological columns support the reservoir abundance map by showing that permeable formations are clearly more developed in the western part than in the eastern part of Oued El Khairat plain. Moreover, this model reveals that a superficial coarse unit extends over a large part of the plain. It includes the shallow reservoirs layers and fosters the recharge of deeper ones. In some localities, it is substituted by clay unit that may have important thickness (case of the KH12, where this unit is 78 m thick), so that the main aquifer is reached at important depths. The clayey layers separating coarse units present also variable thickness, thus having different repercussions on the reservoirs interconnection; it is hindered by their thickening (for instance KH15 and FH boreholes), but fostered by their thinning (for instance, AR and MF boreholes).

Hydrodynamics of the Oued El Khairat aquifer

The piezometric data acquired in 2019 have allowed studying the spatial evolution of the piezometry for the shallow (Fig. 7a) and deep water tables (Fig. 7b).

The piezometric map of the shallow water table shows values ranging from 42 to –1 m/sea level with a gradual decrease from west to east. Comparable values (from 39 to –2.5 m/sea level) and similar evolution are observed for the deep water table. This indicates that the Oued Khairat aquifer is characterized by an E-W groundwater flow and that its recharge occurs mainly in its western part (Zammouri et al. 2006).

The temporal evolution of the piezometry is followed at the KH26 (Fig. 7c) and KH7 (Fig. 7b) piezometers, which present the most continuous measures over the years, respectively for the shallow and deep water tables. Both, KH26 and KH7 show a general piezometry decrease; for example, at KH26, it was 45.79 m/sea level in 2011, but it decreased to 42.3 m/sea level in 2019. A remarkable piezometry increase is noticed in the year 2012; it reached 50/sea level at KH7 piezometer. This increase coincides with a reduction in groundwater exploitation and a rainfall increase inducing significant recharge of the aquifer (Zouaidi 2019).

Passing to the assessment of the transmissivity, which is a determining hydrodynamic parameter to characterize the productivity of an aquifer (Castany 1982; Sen 2015); high transmissivity reflects high aquifer productivity. It is usually determined from pumping tests and corresponds to the product of permeability coefficient (K) and aquifer thickness (Freeze and Cherry 1979). Using this relation, we have deduced and evaluated the permeability values characterizing the Oued El Khairat aquifer.

The available transmissivity measures vary between $0.12 \cdot 10^{-3}$ and $15.6 \cdot 10^{-3} \text{ m}^2/\text{s}$. The highest ones are encountered

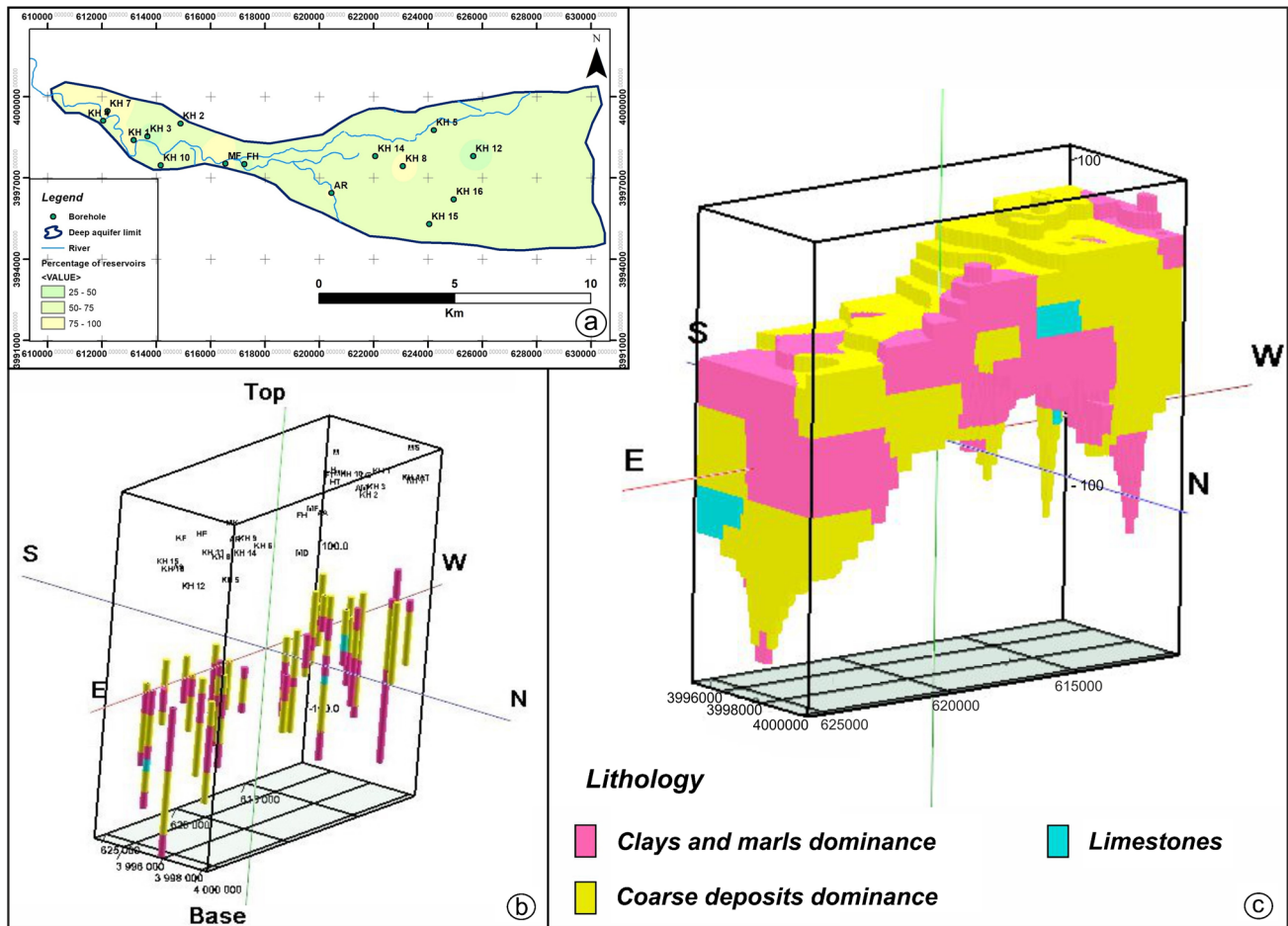


Fig. 6 Arrangement of Mio-Plio- Quaternary coarse formations. (a) Three-dimensional representation of the lithological columns restored using well logs, (b) 3D lithological model of the intersected Mio-Plio-Quaternary series, (c) reservoir abundance map

in the KH 6, KH14, and KH11 boreholes, located in the center-east (Fig. 8a) indicating that this zone presents the highest productivity of the aquifer.

The obtained permeability map (Fig. 8b) exposes values ranging from $0.02 \cdot 10^{-4}$ to $4.3 \cdot 10^{-4}$ m/s. Similar to the transmissivity map, the center-east zone reveals the most elevated values.

In the KH11 borehole showing the best permeability ($4.3 \cdot 10^{-4}$ m/s), the Mio-Plio-Quaternary reservoir formation, thick of 35 m, contains pebbles and gravels (Manaa and Bouasker 1987) having coarse granulometry and large intergranular space. The fact that KH11 is close to a river (Fig. 8b) can explain the occurrence of such sediments; the deposits granulometry decreases while moving away from the river bed (Bravard and Petit 1997). KH 11 is located near the KH8 borehole, which reveals a percentage of 100% on the reservoir abundance map (Fig. 6a).

Unfortunately, we do not have information about the permeability of the Mio-Plio-Quaternary aquifer at the Oued El

Kairat upstream, but logically, it should be high given the richness of this zone in coarse deposits (Fig. 6a).

Quality of the Oued El Kairat aquifer

The water salinity values of the Oued El Kairat deep aquifer (Fig. 9a) range from 1.5 to 3.1 g/l. They show a general gradual increase in salinity in the groundwater flow direction (from the west to the east) (Fig. 7b). Some anomalies are observed, for instance the Fc borehole (3 g/l) is situated further west than the KH36 borehole (2.1 g/l), while it exhibits higher salinity that can be explained by different factors such as Salinization of water is due to the local exploitation rate, water -reservoir rock interaction and the salinity of recharged water (Subba Rao 2008).

Chemical analyzes of the Oued El Kairat deep water, made up at 12 boreholes distributed over the whole plain, were plotted on Piper (Fig. 9b) and Schoeller (Fig. 9c)

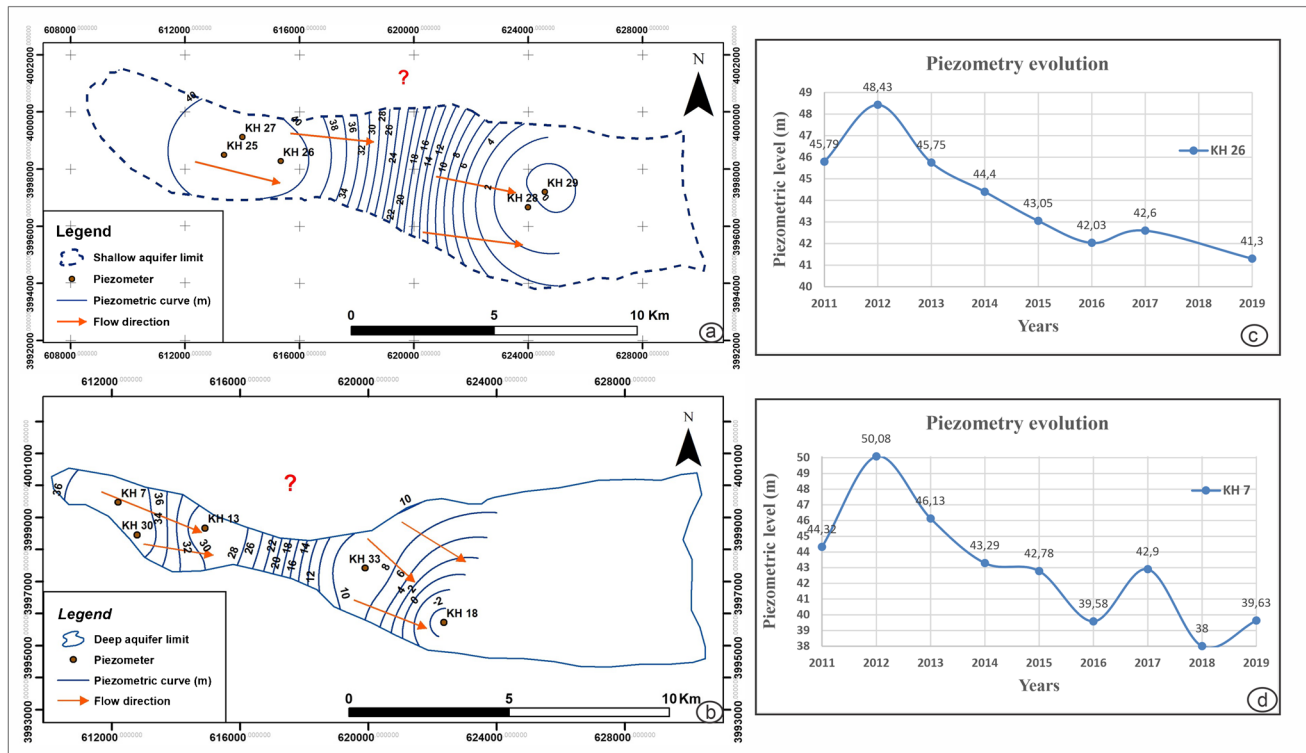


Fig. 7 Spatio-temporal evolution of the piezometry of the Oued El Khairat aquifer system. **(a)** Piezometric map of the shallow aquifer, **(b)** Piezometric map of the deep aquifer, **(c)** evolution of the piezometry of the shallow aquifer over years, **(d)** evolution of the piezometry of the deep aquifer over years

diagrams. They reveal variable concentrations in major elements: Na^+ , K^+ , Ca^{2+} , Mg^{2+} , HCO_3^- , SO_4^{2-} , and Cl^- . SO_4^{2-} , Cl^- , and Na^+ are the dominant chemical elements, indicating sulfate and chloride-sodic facies. In the majority of boreholes, SO_4^{2-} exhibits the highest concentrations that vary between 298 (at KH10) and 1296 mg/l (at KH6). This richness in sulfate may be explained by the dissolution of evaporites minerals and /or sulfide oxidation (Cao et al. 2019; Long et al. 2021). Cl^- concentrations range from 276.9 (at KH10) to 1091.5 mg/l (at KH14). Those of Na^+ are between 194 (at KH10) to 751.5 mg/l (at KH14). Sodium and chloride contents were presumably derived from halite dissolution (Zaczek and Porowski 2017; Mehr et al 2019).

According to WHO's drinking water standards 2017, the guidelines fixed for SO_4^{2-} , Cl^- , and Na^+ are respectively 500, 250, and 200 mg/l; for the different groundwater samples, the Cl^- concentrations exceed the guidelines. Concerning SO_4^{2-} , KH10 (298 mg/l) and KH33 (494 mg/l) boreholes provide water suitable for drinking. It is only KH10 (194 mg/l) for Na^+ .

A previous study of Ketata et al. (2012) dealing with the geochemistry of the Oued El Khairat aquifer has also shown sulfate ion as dominant anion and sodium as dominant cation. This study has revealed that the average TDS (total

dissolved solids) value of the shallow water table ranges from 739 to 2300 mg/l.

Determination of zones suitable for exploitation

The most suitable zones for the exploitation of Oued El Khairat aquifer present the best characteristics relating to its geometry, hydrodynamics and water quality. To determine these zones, we have superimposed the different established maps: the reservoir abundance (Fig. 6a), piezometric (Fig. 7), transmissivity (Fig. 8a), permeability (Fig. 8b), and water salinity (Fig. 9a) maps. The obtained representation shows that the western part of the Oued El Kairat aquifer exhibits the best characteristics (Fig. 10). It presents developed reservoir formations (the coarse layers constitute between 75 to 100% of a 110 thick Mio-Plio-Quaternary series), the lowest water salinities (1.5 to 2 g/l), the highest piezometric levels (30 to 42 m/ sea level) and logically high permeabilities (the Oued El Kairat upstream).

Interesting zones for exploitation occur also in the central-eastern part of the plain; they represent high transmissivity ($15.6 \cdot 10^{-3} \text{ m}^2/\text{s}$) and permeability values ($4.3 \cdot 10^{-4} \text{ m/s}$).

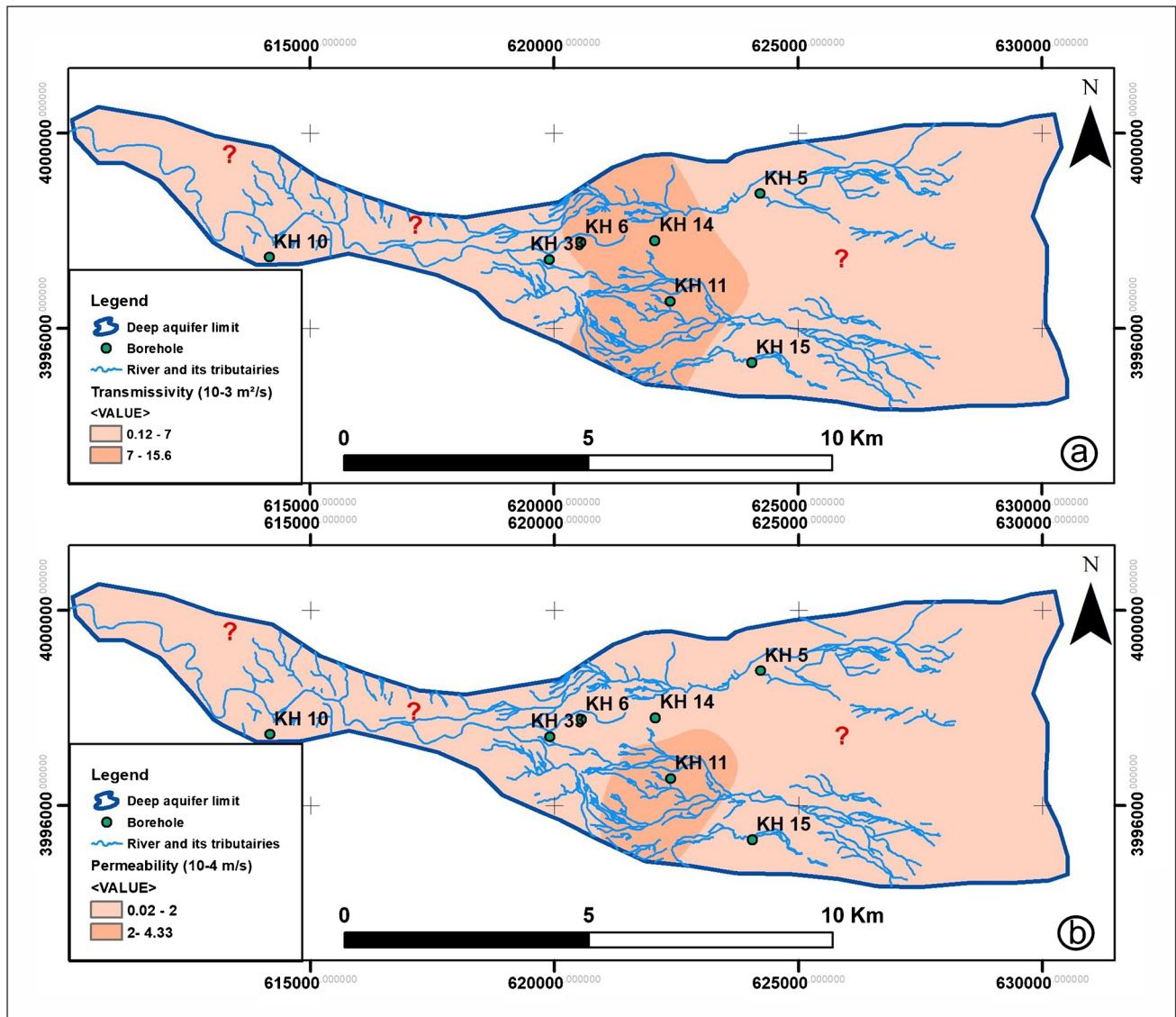


Fig. 8 Transmissivity and permeability maps of the Oued El Khairat aquifer. (a) transmissivity map, (b) permeability map

Conclusion

Diverse data relating to the Oued El Khairat Mio-Plio-Quaternary aquifer: lithological columns, well logs as well as hydrodynamic and hydrochemical measures were integrated using geographical information system (GIS) to define the suitable areas for the exploitation of this aquifer, which constitutes an important resource of groundwater in Enfidha region.

Reservoir abundance map and three-dimensional representation generated from the analysis of lithological columns and well logs highlight that the thickest reservoir formations are encountered in the western part of the Oued El Khairat plain. The established piezometric maps show

that this zone is characterized also by the higher water levels. Besides, it is marked by the lowest water salinity values. So, this zone appears the most suitable for the exploitation of Oued El Khairat aquifer. The central-eastern part presenting high transmissivity and permeability values may be also an attractive zone.

The obtained results can enormously contribute to the management of groundwater in the Enfidha region. They will surely be ameliorated by incorporating other data methods such as vertical electrical soundings (VES) data, which will refine the reconstitution of the aquifer geometry. Additionally, our study can be used as reference of the use of complementary approaches to enhance the groundwater management.

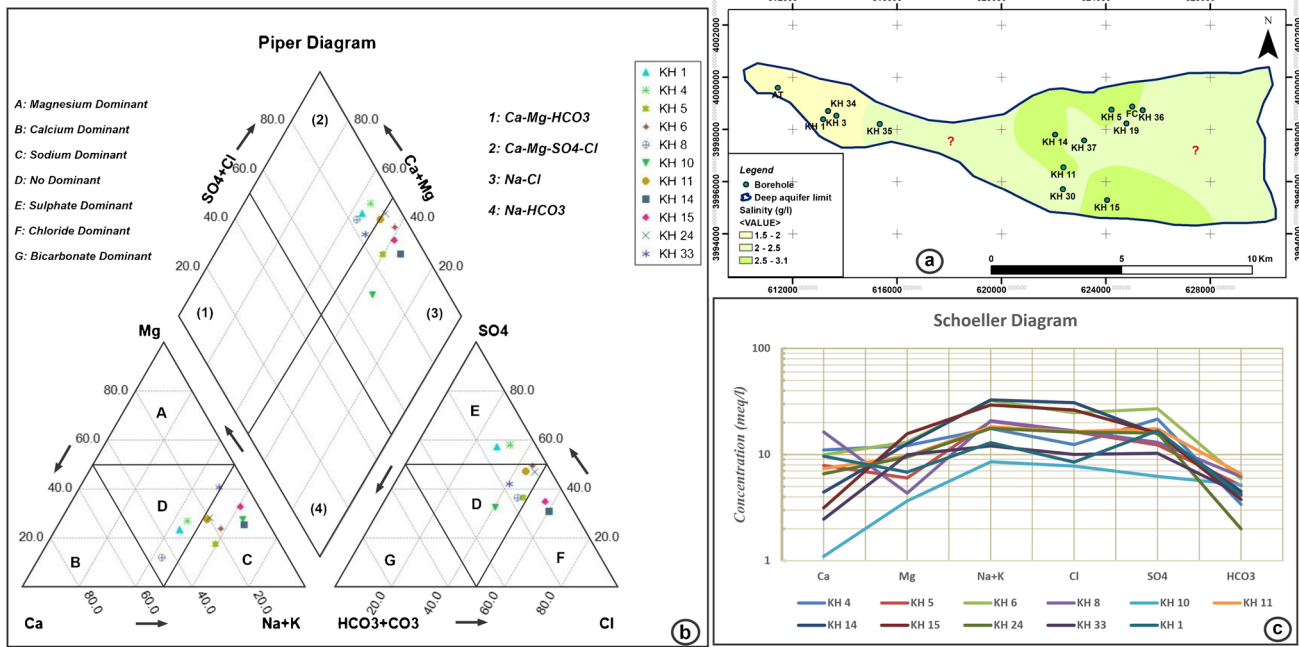


Fig. 9 Hydrochemistry of the Oued El Khairat aquifer. (a) Water salinity map, (b) Piper diagram, (c) Schoeller diagram

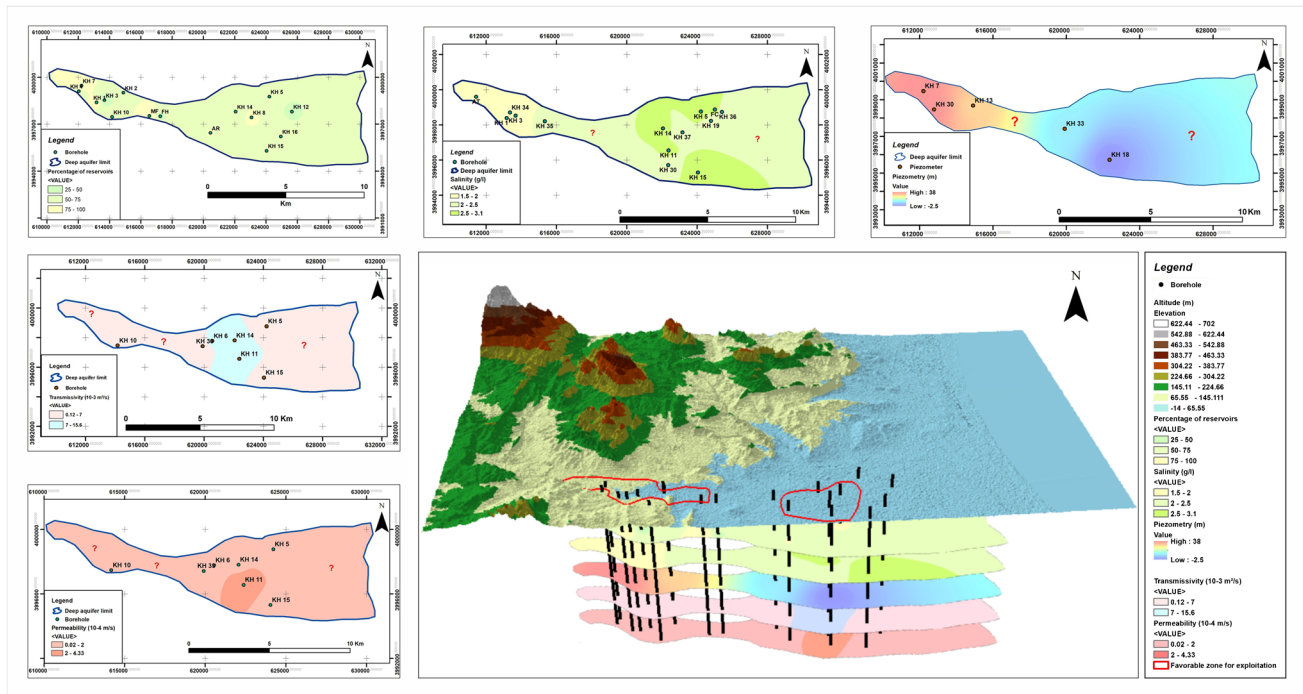


Fig. 10 Identification of the zones suitable for the exploitation of the Oued El Khairat aquifer

Acknowledgements Authors like to thank the two anonymous reviewers for their constructive remarks.

Data Availability The data that support the findings of this study are available on request from the Regional Commissariat of Agricole Development (CRDA) of Sousse and the General Directorate of Water Resources (DGRE).

Declarations

Conflict of interest The authors declare no competing interests.

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